# INFLUENCE OF GRAIN SIZE UPON THE STRENGTH OF STEEL UNDER REPEATED STRESS

BY

ROGER MOORE BOND

A. B. Monmouth College, 1920

---

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

IN CHEMISTRY

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1921

# UNIVERSITY OF ILLINOIS

## THE GRADUATE SCHOOL

June fourth, 1921

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY ROGER MOORE BOND

ENTITLED INFLUENCE OF GRAIN SIZE UPON THE STRENGTH OF STEEL UNDER REPEATED STRESS

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN CHEMISTRY

J. W. [illegible]
In Charge of Thesis

W. A. N[illegible]
Head of Department

Recommendation concurred in*

Committee

on

Final Examination*

*Required for doctor's degree but not for master's

ACKNOWLEDGEMENT

Thanks are due to Professor Herbert Fisher Moore, of the Engineering Experiment Station, and to Doctor Willis Sumner Putman, of the Applied Chemistry Department, for their friendly supervision and their many suggestions. I am especially indebted to Doctor Putman for his exacting personal supervision and his patient efforts to teach me something of the difficult art of micro-photography.

TABLE OF CONTENTS

# INFLUENCE OF GRAIN SIZE UPON THE STRENGTH OF STEEL UNDER REPEATED STRESS

## HISTORICAL

The first investigation of the problem of fatigue in metals was begun by August Wohler[29], "Ober-maschinenmeister" on the Royal Lower Silesia-Brandenburg railway in 1860. The purpose was primarily to solve problems in the design of car-axles and of members of iron bridges, but the investigation was so thorough and basic that it has served as a model for all later investigators and as material for speculation to everyone with a new idea for endurance limit formulae. It included static and endurance tests in torsion, tension and transverse stress with different materials and, in some cases, different shapes. For the transverse stress he used repeated loading and rotating beam machines. The former was a simple beam and the latter a cantilever beam. The rotating beam gave considerable trouble because the specimens were driven into place and frequently broke in the sockets. The speed was about seventy-two revolutions per minute, and one piece was run 132,250,000 cycles without rupture. Bars under load which were run intermittently broke after fewer repetitions than those which had been run steadily. Re-entrant angles made the piece much weaker and a fillet improved the strength at a collar. Merriman[3] gives this summary of Wohler's investigation:

1. By repeated applications of stress, rupture may be caused by a unit-stress far less in value than the ultimate strength of the material.

2. The greater the range of stress, the less is the unit-stress required to produce rupture after an enormous

number of applications.

3. When unit stress in a bar varies from zero up to the elastic limit, the number of applications required to rupture it is enormous.

4. A range of stress from tension into compression or vice versa produces rupture with a less number of applications than the same range in stress of one sign only.

5. When the range in stress in tension is equal to that in compression, the unit-stress that produces rupture after an enormous number of repetitions is greater than one-half the elastic limit.

"Except in fast-moving machinery, this great number (40,000,000) would seldom be exceeded during the natural life of the piece." Wohler.

Wohler concluded that there should be two factors of safety in design of machines: one a proportion between steady load and "limit of fracture", and one a factor for strain or oscillation of load. Bauschinger[3] later conducted investigations which were characterized by the delicate accuracy of his measurements and decided that the endurance limit of material depended upon the "natural elastic limit". From the work of these two men Gerber[6] and Weyrauch and Launhardt[2] evolved formulae for working stress.

The next advance in the study of fatigue phenomena came about 1898 when the microscopic study of metals began to be rather wide-spread. Ewing and Rosenhain[15] subjected pieces of metal to strain in a testing machine mounted on a microscope and established fairly good proof of the statement that the metal yielded by a slipping of the crystals composing its structure along lines of cleavage in the crystals. These slips were indicated on the polished surface of the metal by ridges or "slip bands." Repeated stress increased the number of the slip bands until the

metal gave way by a rupture which extended through the crystal. Repolishing the surface destroyed the slip bands and their existence was challenged by Osmond and Cartaud. Rosenhain[22] by electroplating a polished surface containing slip bands, was able to make a cross section of a series of them and show beyond shadow of doubt that they were formed by the slipping of parts of the crystals along cleavage planes which exist in all crystals.

About the year 1898 a great advance in metallurgy was in progress. In 1868 Mushet introduced the first alloy steel to gain wide use, a tungsten ("self-hardening") tool steel.[1] Fifteen years later chromium came into use as an alloying element and in 1882 R. A. Hadfield discovered how to produce a very valuable alloy steel containing from "7 to 30" percent manganese. In 1899 Taylor and White introduced high speed tool steel. These advances did not change Wohler's tests, with his rotating beam turning seventy-two revolutions per minute. Again, the endurance limit of a piece is worth knowing, for it does not always coincide with the elastic limit as proposed by Bauschinger and the elastic limit is a very elusive quantity, whereas accurate knowledge of the endurance limit makes saving of weight or greater margin of safety possible. The early methods of running endurance tests were very slow and their value was disputed. Andrews[8] cites a long list of railway and steamship accidents which were rather serious and were plainly due to defects in steel axles, propellor shafts or other vital parts. He considered the failures due almost entirely to flaws, sulphide streaks, and other enclosed impurities inherent in the steel, and put his faith in wrought iron. Fatigue investigations were opened along with the microscopic study of the metal which he recommended.

These began to cover a wider field than the earlier ones. The great desideratum was and is a method by which the endurance limit of a steel may be determined in a reasonable time and without prohibitive expense. The uncertainty as to the precise nature of the phenomenon and the doubt in the minds of the investigators of the influence of certain factors, such as speed, rest, range of stress, shock, temperature, form, chemical composition and micro-structure, distribution of stress, previous cold-work, annealing,(of the last two microstructure is the result). This uncertainty and this doubt caused a great variety of tests to be attempted and a great many theories to be advanced, with consequent confusion.

The outstanding work of the period 1896-1911 was that done in England by Reynolds and Smith[20], Stanton and Bairstow[23] on the "throw testing machine" designed by Reynolds originally. The idea was that the rotating beam machines stressed the surface fibers most where the machine they used employed alternate simple tension, and compression for it depended upon the inertia of a cross-head actuated by a crank and connecting rod. When the stress was greatest, as the motion of the crosshead was passing through zero, the friction of the cross-head became negligible. The force of inertia varies as the square of the speed and the stress could be calculated with some accuracy. The speed employed was 800 reversals per minute for Stanton and Bairstow's work, 1000-2000 reversals per minute for Reynolds and Smith's. The range of stress was a little lower for the tests of Reynolds and Smith, perhaps on account of the speed which would influence the friction of the cross-head. The others found that the speed was not an important factor but

that the endurance limit was directly proportional to the percentage of carbon in the steel (which was not heat-treated), and that rapidity of charge of section was vital. Unwin tabulates a test made by Stanton and Bairstow on three bars of Swedish Bessemer steel which had not been broken by more than a million and a quarter reversals at the endurance limit. The bars were broken by static stress, one by compression, two by tension, and the elastic limits corresponded to the range in stress, though both the limit for tension and that for compression had been lowered. Unwin[6] cites this as an example of Bauschinger's suggestion that if the range of stress fell within the "natural elastic limits" the number of repetitions would be unlimited. The suggestion would be valuable if the"natural elastic limits" could be obtained in any way except by endurance tests. Turner[26] attempted to attain the same result by annealing the metal and Moore and Putnam[19] found that the curve of a cold-rolled steel intersected that of the same steel which had been annealed. The endurance limit can be altered by annealing, however, the theory of Bauschinger was purely empirical. It has not been found practicable for determining endurance limits, though a piece might be run a few million revolutions under alternating stress and then broken under static stress if the theory were fundamentally true.

Some of the most valuable work of the period was that of Ewing and Rosenhain[15], Ewing and Humfrey[14], and Rosenhain. The first-named demonstrated the manner of failure of a metal: slip along the cleavage planes of the crystals which compose it. The second-named showed that a repetition of stress produced fracture

by extending and uniting of slip-bands. Stanton and Bairstow applied the results of the former researches to the endurance tests of steel and showed that the results were valid. They also showed that in high carbon steels which have been annealed the path of fracture follows the ferrite grains rather than the pearlite. This is the foundation of the metallographic study of fatigue. Andrews [9] gives some excellent photomicrographic studies of steels which appear to have broken by fatigue and illustrate the fact that fatigue failure may take place after a few hundred repetitions of a stress which exceeds the endurance limit.

The investigation of Eden, Rose and Cunningham [13] in 1911 seems to mark a change in the spirit of attack. They treat the problem as one of commercial importance demanding systematic solution. They used a simple rotating beam instead of a cantilever beam and they plotted their results on logarithmic paper so that their curves were straight lines and more easily dealt with. Upton and Lewis[28] recommended a short time test machine on a different principle but with the definite idea of introducing endurance tests on a large scale, and overcoming the practical difficulties. One advance of Eden, Rose and Cunningham was the high speed which they were able to use, although excessive vibration ruined some tests. They studied the effect of speed, rest, vibration and annealing. They ran a series of specimens with highly polished surface and found that the scratch of a needle on that surface would lower the endurance strength and throw the piece off the stress curve. They experimented with the form of test-piece but the form they used most, had a minimum section between the bearings of the load to induce fracture

where the stress could be more easily computed. In the present investigation the same idea has been employed and improved upon so that failure rarely takes place except in the reduced section which may have a known area and a highly polished surface which is not liable to damage in setting up the machine. The extensity of their investigation was due to the higher speed which permitted the running of a comparatively large number of tests and which did not materially affect the results. There had been other attempts to shorten the time of testing. They usually tried to relate endurande limit to static tests, and, as Upton and Lewis point out, there is no known relation between fatigue and tension. The logarithmic plotting of unit-stress against cycles gave a straight line for the number of cycles used and promised the possibility of obtaining a measure of endurance strength with very few points. Upton and Lewis recommended high stress tests to locate the position and direction of the line. Rosenhain[4] points out that the curve demands a considerable number of points and cannot be accurately located by any single point.

The only American work on the fatigue of metals prior to 1910 that appears in the literature is that of J. E. Howard at the Watertown Arsenal (1898-1910)[17]. Since that time the question has occupied a great deal of attention in America. In 1910 Professor Basquin of Northwestern University gave a paper on the "Exponential Law of Endurance Tests" before the American Society for Testing Materials.[11] The logarithmic plotting of endurance curves appears to be due to him. Moore and Seely[30] gave a logical and mathematical development of the whole fatigue theory, which works very

well except that it throws some doubt on the existence of an endurance limit which later tests have dispelled. The long time tests with loads below a certain amount, run an enormously greater time for a very slightly smaller load, and the curve is practically parallel to the repetition ordinate even when it is plotted on logarithmic paper. One advance from this theory is the definite proof that the endurance limit of a material is apparent when a stress has been found, at which a given specimen will run about four million cycles on a rotating beam machine. Stanton and Bairstow were content with specimens which ran more than a million reversals on their inertia machine, although the conditions were not very like. If a piece is to run practically to infinity the curve must become parallel to the axis along which are plotted the number of reversals of stress. The curve does not reach this value until the piece is capable of running about four million repetitions at the given stress.

In the last five years America has come to the front in the study of fatigue in metals. The problem is to find a method by which the endurance limit of metals may be determined as readily and cheaply as the other physical properties are found in modern plants. It is plain that different metals or different steels have different endurance limits, just as they have different elastic limits, ductility, ultimate strength, coefficient of expansion or electrical conductivity. The difficulty has been that the endurance limit could not be found readily and that it has been considered cheaper and easier to use heavier parts for structures or machines than the limit would demand. But there

is a constantly growing demand for yet lighter, higher speed machines. The automobile and the air-plane were made possible only by the advance in knowledge of the properties of the metals. The automobile built according to the best possible designs of fifty or less years ago would have been flimsy or immovable. The bicycle of that time weighed about four times as much as the modern one and was more fragile. The air-plane was a topic for humorists until an exceedingly light and powerful engine was evolved. The task, in the words of Unwin, is "to determine the minimum amount of material and the best disposition of it in machines and structures to secure safety" [27] The phenomenon of fatigue in metals was brought to light principally by German investigators, Wohler, Bauschinger, Spangenberg, Gerber, Weyrauch and Launhardt. Much of the theory which most satisfactorily explains it, was developed by English engineers and metallurgists, Ewing, Rosenhain, Humfrey, Stanton and Bairstow, Arnold, Stromeyer, Reynolds and Smith and others. Americans may have the opportunity to develop the application of fatigue tests to the point where they will be available for the material and uses which demand them. This was the object of the National Research Council and of the Engineering Foundation when they arranged for a joint investigation of the subject. The machine designed by F. M. Farmer[16], after the suggestion of H. F. Moore, is much more practical than any of the earlier machines for endurance testing, especially on a large scale. The report of the Joint Committee in the Journal of the American Sodiety of Mechanical Engineers in Mechanical Engineering for September 1919 is a very complete and thorough statement of

the various aspects of the problem and provides assurance that it will be taken up from every angle which has shown signs of promise to previous investigators.

## II INTRODUCTORY

The microstructure of metals is certainly a determining factor of their properties. There are three vital points in the study of the microstructure: (1) a means of comparing the structures (2) a means of producing various structures at will, and (3) means of testing the properties of the metal having the specified structure. The first is attained by the microscope and camera combined with chemical analysis. The second may be reached by the aid of the thermo-couple of LeChatelier or the platinum resistance pyrometer, radiation or optical pyrometers, for the structure is affected most by temperature and accurate means of measuring high temperatures is vital. The testing science had a beginning at least in the time of Galileo, but is empirical so far as different materials are concerned. Materials were classified on the locality from which they came in the old days. Later chemical analysis became the fashion but was unsatisfactory because a given material might have a certain analysis and two speciment be opposite in properties. Microstructure seems to be an infinitely better basis for classifying the results of tests and the study as such has been developed within the last thirty years, by such men as Osmond, Rosenhain, Stead, Roberts-Austen, Roozeboom, Howe, Saveur, LeChatelier, Carpenter, Arnold, Heyn, Benedicks, Martens and Sorby.

The factors influencing the growth of the crystalline grains in any metal have been given a great deal of attention. Ewing and Rosenhain showed that the crystals of lead grow at room temperatures though not unless they have been deformed by strain. They explained the action as electrolytic. The "eutectic cement" theory, which they advanced, stated that even in very pure metal there was enough impurity to form a eutectic around the boundaries of the crystals. Any deformation caused contact of two crystals and thus the establishment of an electrical circuit, which by electrolysis (from the difference in potential between the contact junction and the solution junction) transferred matter from one crystal to another. The theory seemed plausible and was beautifully illustrated by an experiment with lead, but has not been generally adopted and Rosenhain and Ewen [23] later brought forth some experiments of metal which, they claimed, could not have enough impurities to form a eutectic. Stead performed some experiments on ferrite in 1898[5] which indicated that crystals of iron containing less than 0.15% carbon would grow on annealing below the critical temperature. Sauveur[5] gives some photographs on 0.05 % carbon steel which had been subjected to a stress varying in intensity throughout the section, and then annealed at 650° Centigrade seven hours, before it was photographed. He also gives a test by C. Chappell with a picture of brass broken by tension and annealed. The piece was tapered toward the center so that the unit stress varied from the center to the ends. There were three zones of crystals. Those in the center had been very severely stressed and were very small and those toward the end

which had been very slightly stressed were smaller yet. Those in the center were very large, indicating that a critical stress was necessary to produce growth.

Carpenter and Elam[12] give a highly satisfactory theory of crystal growth and a large amount of evidence to substantiate it. "Crystal growth," they say, is the re-arrangement of certain crystals in a crystal aggregate to conform with the orientation of certain other crystals during which process the latter increase in size by the addition of re-oriented material at the same time as the former decrease in size by the same amount." "Recrystallization" is the "complete re-orientation of a crystal or a group of crystals." It starts from new centers, is quite independent of the old system of orientation, is characterized by a refined structure and is complete when all traces of the old system disappear. The alloy which they used to demonstrate the manner of crystal growth was comparatively easy to obtain and to study. A picture of a specimen which was prepared in this laboratory is shown in this thesis. The theory is that there are three factors which are concerned with the growth of crystals in any metal. These are time, temperature, and amount of plastic deformation. There can be no growth in which all these are not included, though in general, the last has been slighted. They proved that metal which has not been plastically deformed does not increase in grain size and that for equal time and equivalent temperature the amount of growth is determined by plastic deformation of the crystals. For the same deformation the amount of growth is determined by the time and temperature. The explanation for

Chappell's experiment is that the crystals in the center had been strained enough to start re-crystallization, while those on the end had not been strained enough to start growth and those between had been strained sufficiently to grow. If the piece had been annealed at a lower temperature it would have shown a larger area of unchanged crystals, and a smaller area of recrystallization while the area of growth would have been about the same. If it had been annealed at a higher temperature the area of recrystalliaation would have been larger. "The higher the temperature, the less the deformation required to produce crystals of the maximum size obtainable at that temperature."

There seems to have been no formal investigation of the fatigue strength of the metals on the basis of grain size, though the authorieies who mention the subject of this research are positive that the endurance strength decreases as the grain size increases. For example, Upton[7] in Materials of Construction, says, (P. 112) "in the case of the piece failing in service when similar pieces stand up, the original crystal size of the piece which failed was larger." In the report of the Joint Committee[25], which suggested the problem, Rosenhain[16] is quoted:

"The question then arises whether the increased size of crystals produced in a simple metal by prolonged heating is injurious or otherwise, so far as the useful properties, and more especially the mechanical properties of the metal are concerned. There can be little doubt that within reasonable limits the mechanical propérties of a simple metal are better, the smaller the constituent crystals of which it is built up. Under the tensile test, coarseness of structure usually results only in a slightly lowered yield point, while the ultimate stress and the elongation are little impaired, although the reduction of area at fracture is sometimes markedly less. On the other hand, under both shock and fatigue tests, a coarse structure, even in a simple metal gives unsatisfactory results."

## III. THE PROBLEM

The problem of this research is simply to produce a uniform grain size in several groups of specimens of the same steel, so that the groups will be alike except for grain size, and to determine the stress at which each group will withstand an infinite number of repetitions of the stress. The results should display the relation, if any, between grain size and endurance strength.

## IV. THEORETICAL SOLUTION

It has been stated that repeated stress causes deformation of the crystals which compose the metal through the formation of slip-bands in the crystals. The pictures by Professor Moore demonstrate this vividly. He has obtained motion pictures of the polished surface of a specimen which was being bent alternately back and forth. The rate of bending was slow enough to permit observation, but the straining of the metal was so severe that a crack was developed. The deformation of the crystals was striking for they shifted like an old wooden box, but more striking, because otherwise invisible, was the action of the boundaries. They appeared to be perfectly elastic and the crack developed in the crystal proper.

When the stress is so great that the crystals are deformed a quantity of energy must be transformed into heat, for the movement of the slip-planes certainly involves friction; but if the crystal boundaries are elastic they would not cause any heating effect. The motion caused by stress below that necessary to deform a considerable number of crystals would not cause the evolution of

heat and should not induce failure even with an infinite number of repetitions of stress. The work done in the plastic deformation of metal is, then, transformed to heat, by the motion along the slip-planes, but if the crystals are very small the area of the boundaries is great in proportion to the area of the crystals, and the stress should be taken up by the elastic boundaries so that a greater stress should be required to deform the crystal and thus to induce failure under repetition of stress. If the composition of the crystals is such that they have the same resistance to deformation as their boundaries, the metal should not fail through fatigue at a stress much below its ultimate strength. If the crystals are stronger than the boundaries the larger crystals should be stronger.

As to the evolution of heat when a metal is stressed repeatedly above its endurance limit, such a phenomenon has been observed. Turner[26] observed it and Stromeyer[25] made an investigation along that line, while Moore and Harsch have recentil announced a method for finding the endurance limit by careful measurement of the temperature rise for stress above the endurance limit. Probably there is some heat evolved for very low stresses, but the increase when the endurance limit is passed indicates the truth of the assumption from the evidence of the pictures and the hysteresis experiments of Bairstow[27]. The strength of the crystals relative to their boundaries is a varying quantity depending upon the material. Professor Moore states that a troostitic steel which was tested had an endurance strength nearly equal to the elastic strength and that very pure iron had the same property. Troostite is different from ferrite in almost every way but the ratio of the

strength of the boundaries to the strength of the crystals is the same, the strength in fatigue should be the same proportion of the ultimate strength in each material. Certain impurities tend to segregate in the boundaries and alter the strength and often make the material "brittle." Supposing that the relative strength of the crystals and the boundaries could be determined ( and it should be possible to strain the piece on the microscope and determine whether the fracture went through the crystal or followed the boundaries) it should be possible to determine the endurance strength of the material microscopically, by noting the areas of crystals, and consequently the proportion of boundaries.

For a pearlitic steel with comparatively large crystals the increase produced by doubling the area of the average crystal should not produce a comparable decrease in the strength, because the proportional area of the boundaries was small in the first place. For a sorbitic or martensitic steel the difference should be considerable. This paper is concerned only with a pearlitic steel with large grain size throughout.

## V. METHOD OF ATTACK.

### A. Selection of Specimens.

The material used was in the form of half-inch rods of cold rolled steel containing about 0.20% carbon. The speciments were thirteen inches long and were designated by the number of the steel in the main investigation (52), the letter assigned a bar( A, B, C, or D), and a number denoting their location in the bar(0, 13, 26, 39, 52, 65, etc.). For example, 52A 104 was the piece cut from bar A after 104 inches had been cut off for other specimens.

Then the bars were arranged as they were originally and the specimens for the three series of tests were selected so that any difference due to difference between the chemical composition of the bars would be balanced, so far as possible. In one test a specimen from A ran out, in another test, one from B and in the third, one from C. The first two were from the end of the bar from which they came and the last from the middle. Apparently the location did not have a very great effect.

B. Method of Heat-Treatment.

Trials were first made of the grain size that could be produced. Small pieces, one inch long, were heated in an electric furnace to varying temperatures for varying periods of time. One series was normalized by heating to 930° Centigrade fifteen minutes. Another was heated to the same temperature one hour and another eight hours. During the one hour treatment an attempt was made to learn the critical points of the steel by recording the temperatures during the heating. The temperatures throughout the research were measured by means of a Pt - PtRd thermocouple and a potentiometer made by the Pyrolectric Instrument Company. It was calibrated against a standard noble metal thermocouple and checked with it during the year, showing that the two had not changed relatively. During the investigation, also a freezing point of NaCl was found at 810° Centigrade. The principal use of the instrument was to deep the temperature constant and to give a rough estimate of the actual temperature. It was sufficiently accurate for the purpose.

The trial pieces were polished, etched with a solution of nitric acid in absolute alcohol, 4% strength, and photographed at a convenient magnification which was 88 diameters. The treatment

which lasted eight hours appeated to give a very marked difference in grain size and twelve of the thirteen inch rods were given that treatment, while twelve were normalized. The fatigue tests showed that the series with the lower grain size had a slightly lower endurance limit. Therefore a third test was performed to obtain a still larger grain size. After six trials one was found which appeared to be satisfactory (121). But the other specimens had been heated in an electric furnace which could not be used at more than 1000° Centigrade and it was necessary to heat them in a coal fired muffle furnace. The furnace could not be raised to a higher temperature than 1100° Centigrade and could not be maintained long at that temperature. The specimens were packed in $Al_2O_3$ so that they cooled very slowly and the grain size developed was fairly large. The Equilibrium Diagram shows the location of another series of treatments which have not been tested but have been experimented upon.

C. Testing of Specimens.

The endurance tests were all performed in machines of the type designated by Mr. F. M. Farmer and described by him in the Proceedings of the American Society for Testing Materials for 1919. The stress diagram of this machine is shown on the next page and is little more simple than the design of the machine itself. The specimens were ground to size and then the central section was turned down to a minimum diameter of 0.3 inch. The portion removed was a segment of a ten inch circle so that there would be no sudden reduction of area. The machines consisted of a bed with an adjustable bearing carrying a pulley and half a flexible coupling at one end. Four short sleeves running in ball-bearings were

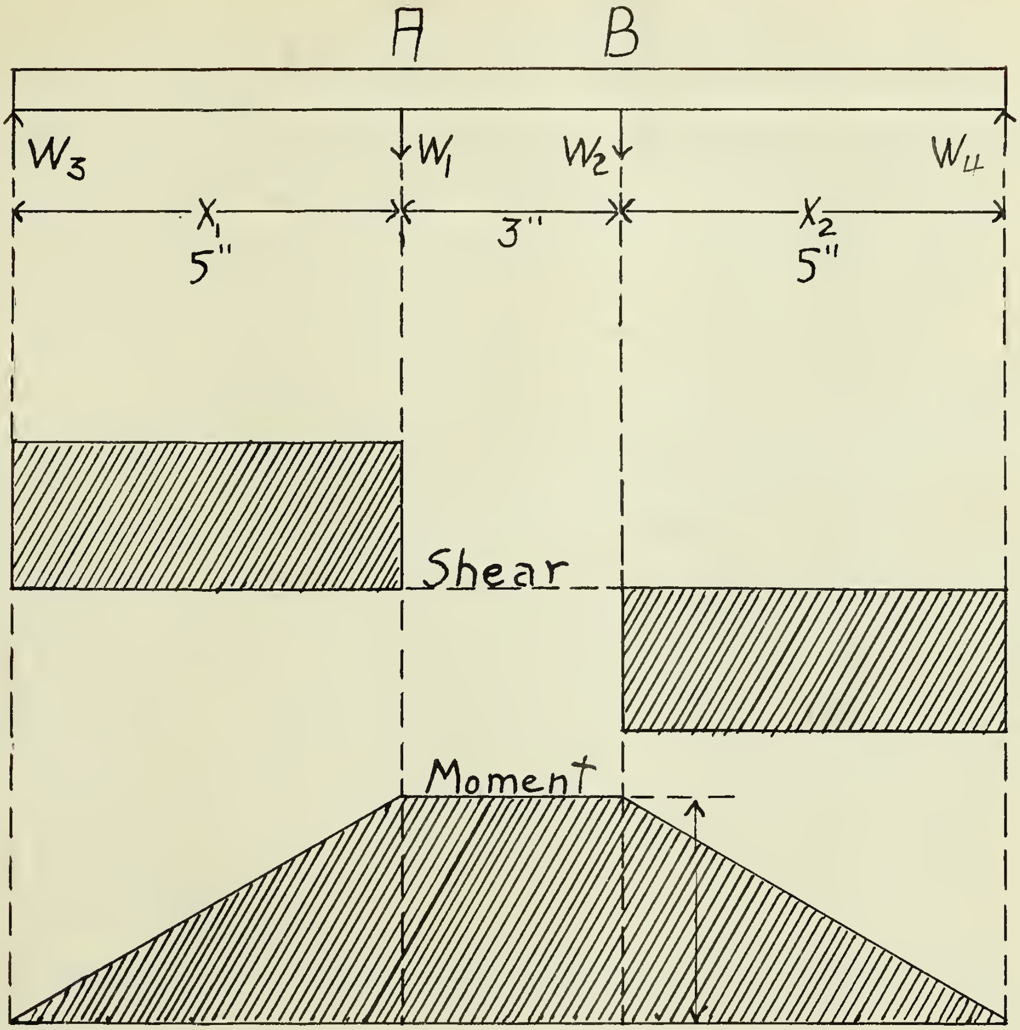
placed on the specimen. Trunnions of the two end bearings supported the specimen in the machine and similar trunnions on the center bearings supported yokes which held the weights. One end sleeve formed the other half of a flexible coupling to the one carried on the pulley-shaft and the other was joined by means of a link to the reducing gear of a revolution counter. The specimen was thirteen inches long. The centers of the end bearings were set on marks eleven inches apart and those of the center bearings on marks three inches apart. The weight of the center bearings and that of the weight carrier was very accurately 34 pounds in each case. The standardization of the machines made it possible to use any machine without producing discordant results. The stresses shown in the tables in this report were obtained from tables showing the diameter of the specimen and the unit-stresses for loads in increments of five pounds. These tables have been checked over and are in constant use in the laboratory.

The first specimens were put in at a stress which was expected to break them in a short time. The machines ran about 1500 revolutions per minute with little vibration. The soft annealed specimens were easily bent and had to be set very carefully. A slight bend or excessive vibration appeared to have more effect than any difference in grain size, that could be obtained. However every specimen which broke or cracked,failed at the minimum section. As soon as a point on the endurance curve was obtained it was plotted on logarithmic paper posted on the wall of the laboratory for convenience and, the next specimen


The Farmer Type Reversed Bending Machine

A is the specimen.
B, C, D, and E are ball-bearings. The specimen is set in the sleeve which runs in B. Each bearing is mounted with trunnion pins. Those of B are set in a notch and the pins of C, D, E are centered on scratches on the bar. C and D are carried by A.
H is a flexible coupling.
K is the electric driving motor and pulley.
M is a yoke connecting the yokes supported by the trunnions of C and D.
N is a revolution counter connected to the specimen by a flat link and reducing gear. The link is set as loosely as possible.
W is the weight. A frame was used and weights hung upon it.
C, D, M and W with the connection CD and the spring between M and W weighed thirty-four pounds within a tenth of a pound. The W of the formula in the diagram following this page is equal to half the total weight.

STRESS DIAGRAM OF FARMER TYPE REVERSED BENDING MACHINE




$W_1 = W_2 = W_3 = W_4 = W$
$x_1 = x_2 = x$

The moment between A and B is uniform and has a maximum value of Wx
The beam has a circular section, but the section AB has a radius turned from it to increase the fiber stress there.
Maximum fiber stress between A and B: $S = Mc/I =$

$$\frac{Wx}{1/32 = d^3} = \frac{Wx}{0.0982\ d^3}$$

Where S = stress in outer fibers lbs/in²
M = bending moment lb.- in
c = distance from neutral axis= d/2
I = moment of inertia of section.

was run at a stress which might be expected to cause it to fail after a certain number of cycles. The point lay practically in a straight line until the number of cycles approached four million when the line became horizontal, indicating that the specimen would run indefinitely at that stress. The stress at which a specimen would run ten million cycles was designated as the endurance limit. The machines were run day and night, continuously until the specimen broke, striking a trigger which caused the switch of the motor to be opened and the machine stopped. Then the difference between the initial and the final readings of the counter gave the number of cycles the specimen had run. According to Basquin's law[11] $S = KN^m$ where S is the maximum fiber stress, N is the number of repetitions necessary to cause failure, and K and m are constants.

D. Study of Microstructure.

One specimen from each test, (52 C 104 and 52 D 0) was photographed microscopically after it had been broken. First a longitudinal section of the section of greatest stress was polished, etched and examined. In each case it showed a banded structure like that due to cold working. A cross-section from the unstressed end gave a ground for comparison of grain-size. A longitudinal section from the unstressed end showed very much the same banded structure as the center did although it was a little less pronounced. It was concluded that the annealing had not destroyed the distorted structure due to the original cold-rolling of the steel.

E. Grain count.

A piece of ground glass was fitted to a plain glass frame which fit the back of the camera, the magnification changed to 100 diameter, as closely as it could be obtained(and maintained constant) and a circle 79.8 millimeters in diameter, as recommended by Zay Jeffries, was drawn upon it. It was much easier to count the crystals upon the ground glass than upon a photograph because it was always possible to adjust the focus so that a doubtful line could be identified as a grain-boundary or not, but it was not easy to make an accurate count. The crystals appearing within the circle were checked off by means of a pencil mark on the ground glass. Then the crystals which touched the circle on either side were counted, their number divided by two and added to that of the crystals wholly inside the circle. The ground glass was then removed and the number of pencil marks counted. They should check closely with the total number of grains counted. If they did not, the count was necessarily repeated from the beginning. After a consistent count had been obtained the area was photographed.

The series which had been heated to 930° C eight hours lacked uniformity. The best explanation that can be found is in Carpenter and Elam's paper on "Crystal Growth and Recrystallization in Metals." There were evidently several degrees of stressed grains,only a few had been strained sufficiently to grow at 930°. Most of the crystals had been strained enough to start growth at 1050°. The largest crystals in the eight hour treatment were nearly as large as any in the 1050° treatment while the smallest were like the smallest in the fifteen minute

treatment. There were not quite so many small crystals but they were so small in comparison with the large ones, that they could not be imagined as influencing the properties very much, thus the grain-sizes were not so widely different as they would appear to be in the pictures nor so much as the grain-count would indicate. For this reason the grain count is not to be trusted in all cases. If all the grains are counted, and the attempt was made, the results are somewhat misleading while if the important ones only are counted a very puzzling distinction is introduced. It is rather doubtful whether any two men could count the crystals in a given area and arrive at results that agreed closely, though the accuracy depends largely upon the type of structure.

To compute the area of the average grain: A circle of 79.8mm. diameter has an area of 5000 square millimeters. The magnification was 100 diameters. Therefore the area represented by the circle was 5000/10000 or 0.5 $mm^2$. This equals 500,000 square micro-millimeters or "$mu^2$". Then 500,000/number of grains counted gives average area in "$mu^2$". Table IV shows the results of the count. A specimen from each bar used in the test of each series was examined. The cross -section from the end was adopted except in the case of 52 C 39 where a cross-section from the center was used and showed no great variation from the grain size of 52 C 52.

## VI. CONCLUSION.

The endurance limits, found by means of the Farmer type reversed bending machines, were less as the grain-size increased but this difference was rather small for the steel and structure

used, and not so great as other factors, such as bending previous to the test and vibration in the machine.

It is suggested that the influence of grain size depends upon the proportional area of boundaries to crystals, and that in the steel used the smallest grain-size contained a small proportional area of grain-boundaries which could not be much less in the largest size.

For a higher carbon steel with a different structure or containing different impurities the difference in fatigue strength due to grain size might be different, due to a difference in the relative strength of the boundaries.

# TESTS ON FARMER TYPE REVERSED BENDING MACHINE

## TABLE I

0.20% C, Cold-rolled steel, heated to 930° C. 15 minutes.

| Number | Dimensions (inches) | Load (lbs) | Mch. | Cycles | Unit-stress (lbs/in²) |
|---|---|---|---|---|---|
| 52A52 | 0.300 | 50 | 11 | 54,200 | 37,720 |
| 52B39 | 0.295(5) | 46 | 11 | 89,300 | 36,310 |
| 52B26 | 0.300(4) | 46 | 11 | 112,600 | 34,700 |
| 52C78 | 0.295(5) | 43 | 11 | 250,600 | 33,925 |
| 52C26 | 0.300 | 44 | 11 | 271,300 | 33,190 |
| 52B13 | 0.297- | 41 | 11 | 544,100 | 31,879 |
| 52C 0 | 0.299 | 41 | 11 | 624,100 | 31,240 |
| 52C104 | 0.297(5) | 40 | 11 | 708,300 | 30,945 |
| 52B91 | 0.298 | 38 | 11 | 871,600 | 29,250 |
| 52A 0 | 0.300 | 40 | 11 | 1,188,200 | 30,180 |
| 52A104 | 0.299(4) | 39 | 11 | 2,559,100 | 29,718 |
| 52A143 | 0.299 | 36 | 12 | 10,719,700 | 28,956 |

## TABLE II Same heated to 930°C 8 hours.

| Number | Dimensions | Load | Mch. | Cycles | Unit-stress |
|---|---|---|---|---|---|
| 52C91 | 0.300 | 54 | 11 | 500 | 40,738 |
| 52B104 | 0.299 | 51 | 12 | 2,800 | 38,860 |
| 52B78 | 0.298 | 49 | 12 | 79,800 | 37,700 |
| 52C13 | 0.298(5) | 47 | 11 | 96,400 | 35,995 |
| 52A39 | 0.300 | 45 | 11 | 189,900 | 33,948 |
| 52B52 | 0.299 | 42 | 11 | 281,300 | 32,000 |
| 52A13 | 0.297(5) | 40 | 12 | 829,400 | 30,789(start. |
| 52A117 | 0.297(5) | 35 | 12 | 1,082,100 | 27,080 bent at/ |
| 52A130 | 0.299 | 39 | 12 | 1,160,800 | 29,718 (start. |
| 52A65 | 0.299 | 36 | 12 | 3,805,100 | 27,430bent at/ |
| 52D 0 | 0.299 | 37 | 12 | 3,307,900 | 28,194 |
| 52B 0 | 0.297 | 34 | 12 | 10,413,700-- | 26,400 |

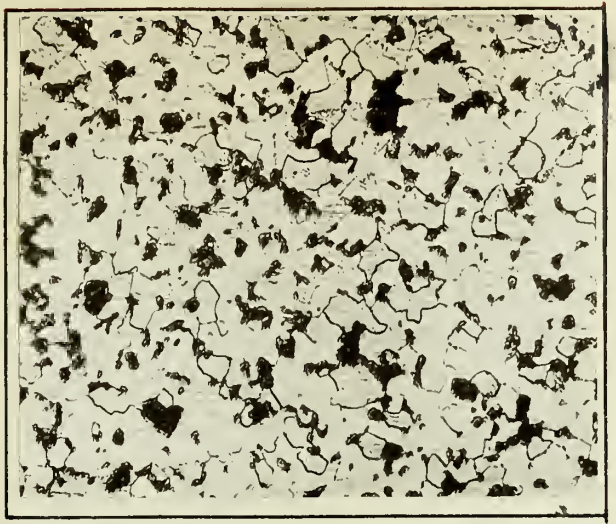
## TABLE III Same steel heated to 1050°C. 4 hours.

| Number | Dimensions | Load | Mch. | Cycles | Unit-stress |
|---|---|---|---|---|---|
| 52A91 | | | | | |
| 52A91 | 0.301 | 40 | 12 | 994,700 | 29,877 |
| 52B65 | 0.298(5) | 37 | 12 | 2,379,400 | 28,337(start. |
| 52C39 | 0.299(5) | 35 | 12 | 3,002,000 | 26,530bent at/ |
| 52C52 | 0.299(5) | 36 | 12 | 3,774,000 | 27,295 |
| 52A78 | 0.300 | 35 | 6 | 2,709,800 | 26,400 |
| 52C65 | 0.298(5) | 34 | 6 | 10,861,400-- | 26,040 |

TABLE IV

Showing comparative grain sizes of the specimens tested.

| Number of piece | Grains in 79.8mm. circle | Area of Grains ($mu^2$) | Variation | | Group. |
|---|---|---|---|---|---|
| 52A104 | 580 | 864 | 7 | 0.8% | |
| 52B91 | 593 | 844 | 13 | 1.5% | Table 1 |
| 52C104 | 580 | 864 | 7 | 0.8% | |
| Mean | 584 | 852 | | 1.5% | |
| 52A13 | 407 | 1228 | 307 | 20.0% | |
| 52B52 | 323 | 1546 | 11 | 1.0% | Table II |
| 52C13 | 290 | 1725 | 190 | 12.4% | |
| 52D 0 | 305 | 1640 | 105 | 6.7% | |
| Mean | 336 | 1535 | | | |
| 52A76 | 189 | 2645 | 250 | 8.6% | |
| 52B65 | 189 | 2645 | 250 | 8.6% | Table III |
| 52C39 | 161 | 3110 | 215 | 7.5% | |
| 52C52 | 157 | 3180 | 285 | 9.9% | |
| | 174 | 2895 | | | |



Number 52 A 104, (x100)

Grain Area - 864 mu$^2$

Unit Stress -

29,718 lbs/inch$^2$

Cycles - 2,559,100

Cross-section from end

Number 52 C 39, (x100)

Grain Area - 3110 mu$^2$

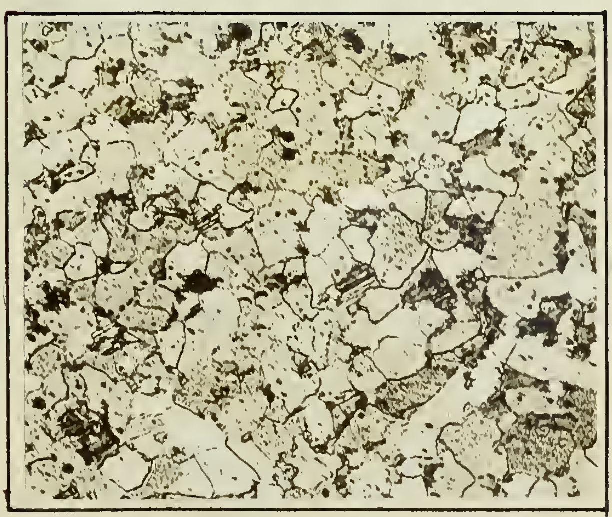
Unit Stress -

26,533 lbs/inch$^2$

Cycles - 3,002,000

(Bent at start)

Cross-section from center



Number 52 D 0, (x100)

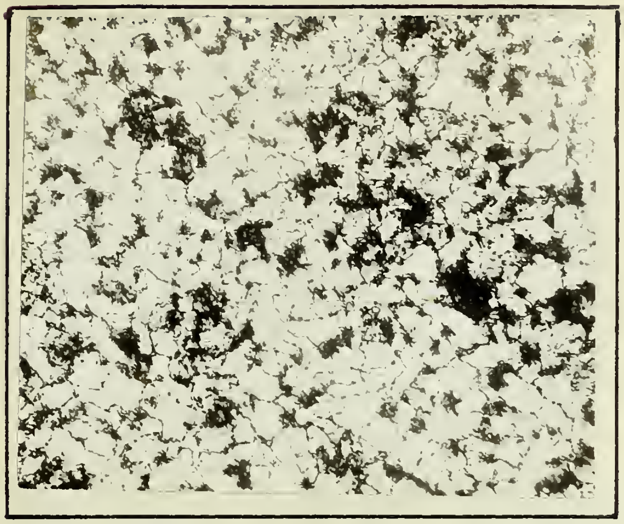
Grain Area - 1640 mu$^2$

Unit Stress -

28,194 lbs/inch$^2$

Cycles - 3,807,900

Cross-section from end



Number 52 B 91, (x100)

Grain Area - 844 $mu^2$

Unit Stress -

29,250 lbs/inch$^2$

Cycles - 871,600

Cross-section from end

Number 52 C 104, (x100)

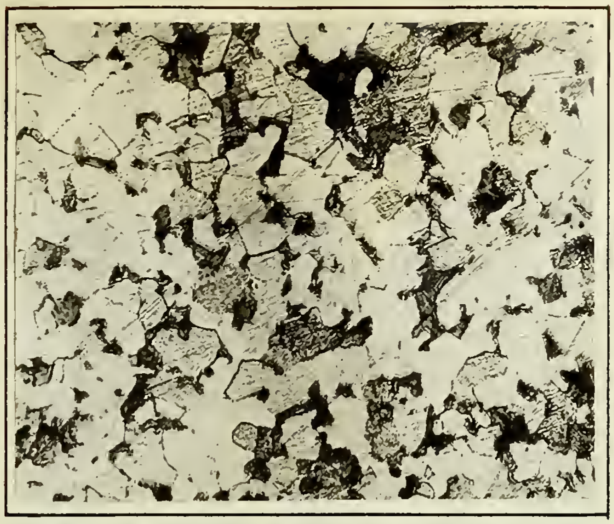
Grain Area - 864 $mu^2$

Unit Stress -

30,945 lbs/inch$^2$

Cycles - 708,300

Cross-section from end



Number 52 B 52, (x100)

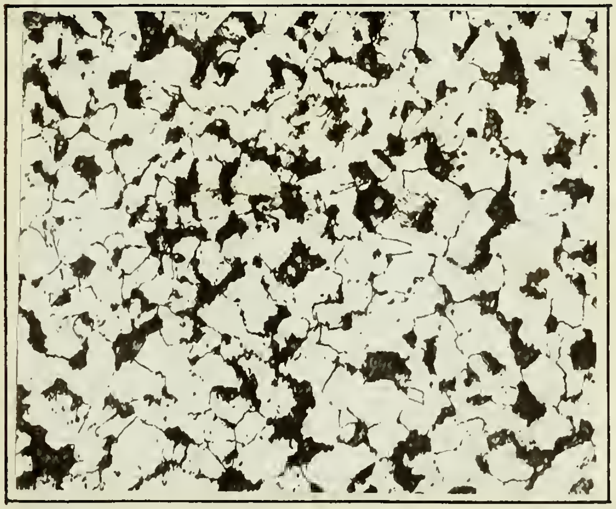
Grain Area - 1546 mu$^2$

Unit Stress -

32,004 lbs/inch$^2$

Cycles - 281,300

Cross-section from end



Number 52 A 13, (x100)

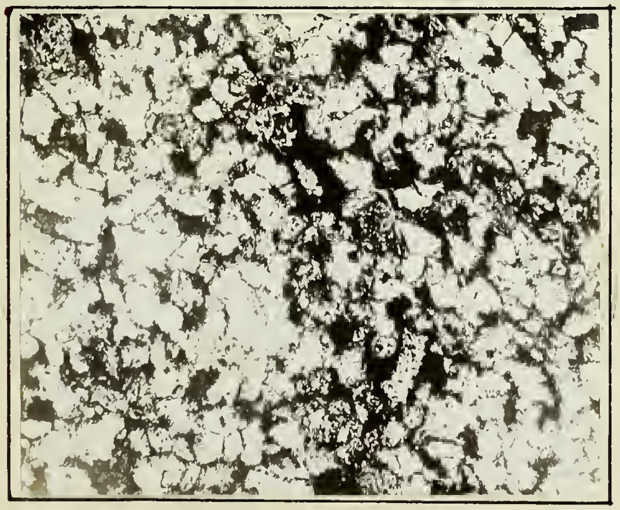
Grain Area - 1225 mu$^2$

Unit Stress -

30,789 lbs/inch$^2$

Cycles - 829,400

Cross-section from end



Number 52 C 13, (x100)

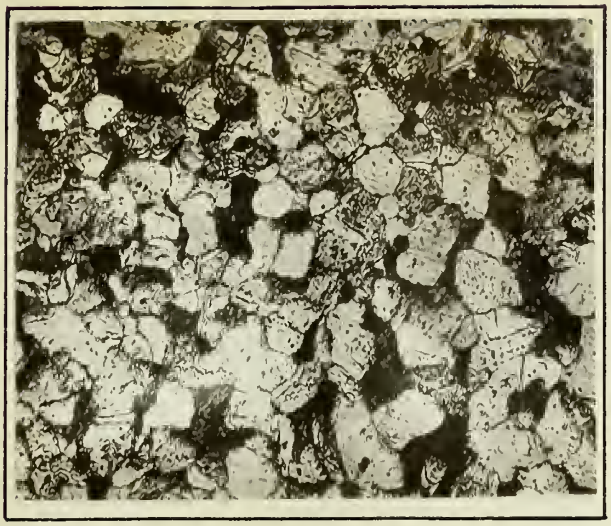
Grain Area - 1725 mu$^2$

Unit Stress -

35,995 lbs/inch$^2$

Cycles - 96,400

Cross-section from end



Number 52 C 52, (x100)

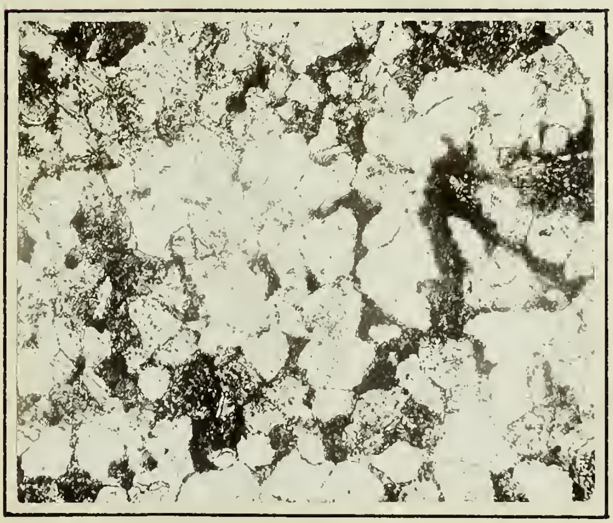
Grain Area - 3180 mu$^2$

Unit Stress -

27,995 lbs/inch$^2$

Cycles - 3,774,000

Cross-section from end



Number 52 A 78, (x100)

Grain Area - 2642 mu$^2$

Unit Stress -

26,400 lbs/inch$^2$

Cycles - 2,709,800

Cross-section from end

Number 52 B 65, (x100)

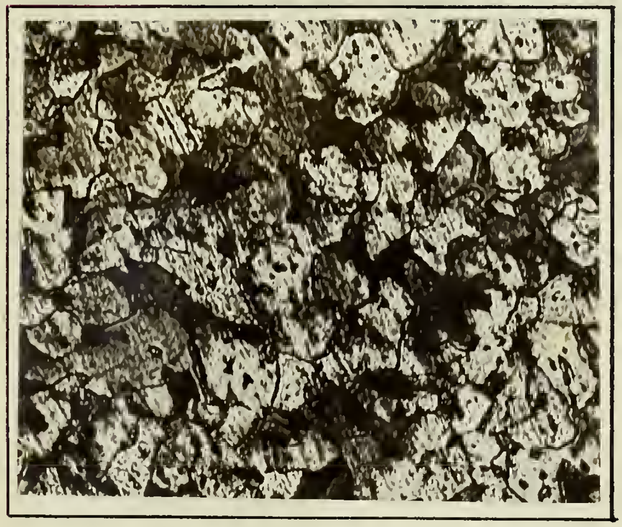
Grain Area - 2642 $mu^2$

Unit Stress -

28,337 $lbs/inch^2$

Cycles - 2,379,400

Cross-section from end



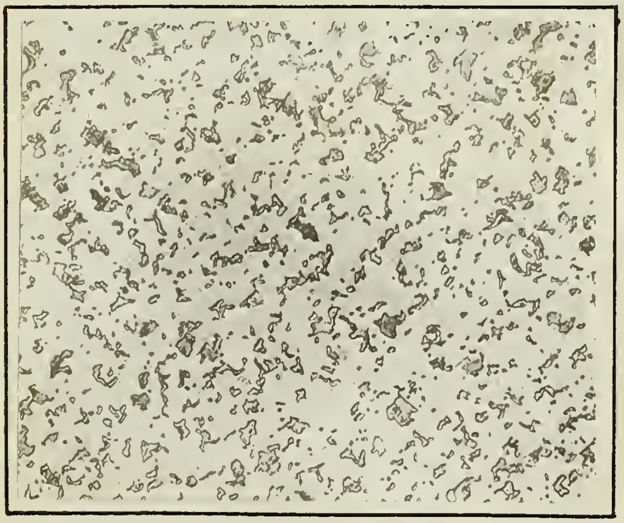
Number 52 B 65, (x100)

Not used for grain count

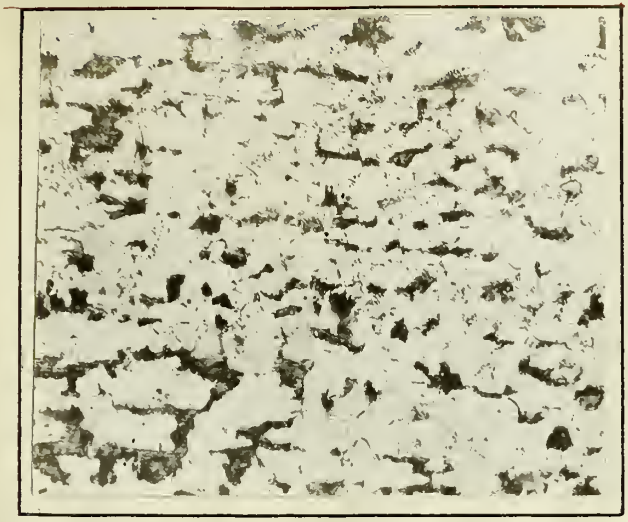
Different area on the same surface to show uniformity

Study of two Farmer machine specimens.

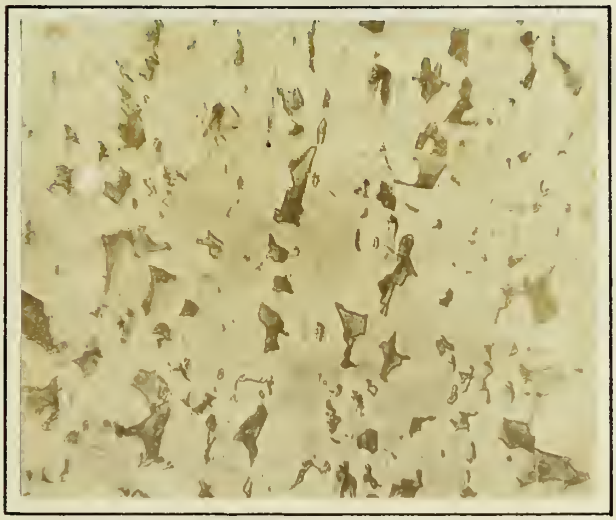
Number 52 D 0, (x88)
Cross-section from
end, unstressed



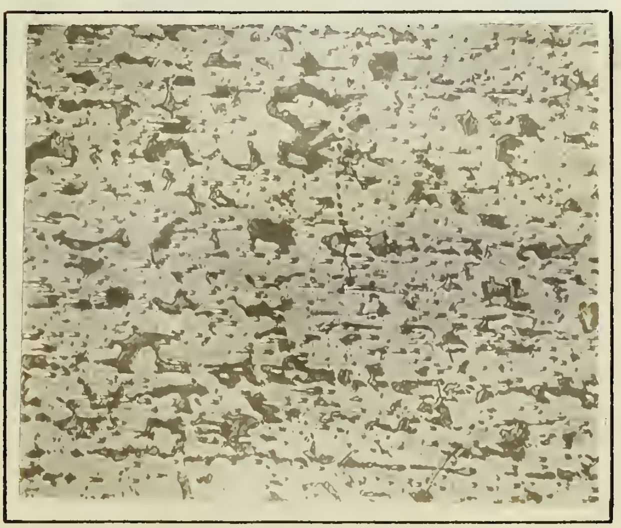
Number 52 C 104, (x88)
Cross-section from
end, unstressed



Number 52 D 0, (x100)
Longitudinal section through end, where moment was small. Banded structure due to rolling.



Number 52 D 0, (x38)
Longitudinal section through center, where moment was at a maximum.
Banded structure longitudinal.

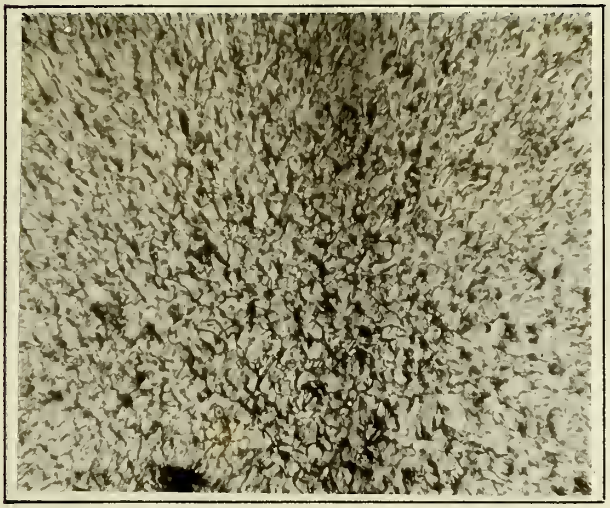


Number 52 C 104, (x88)
Longitudinal section through center. Maximum stress.

Number 52 DO, (x100)

Longitudinal area through center at magnification used for grain count.

Heat- Treatments of Steel
1. 0.20% C, cold-rolled.



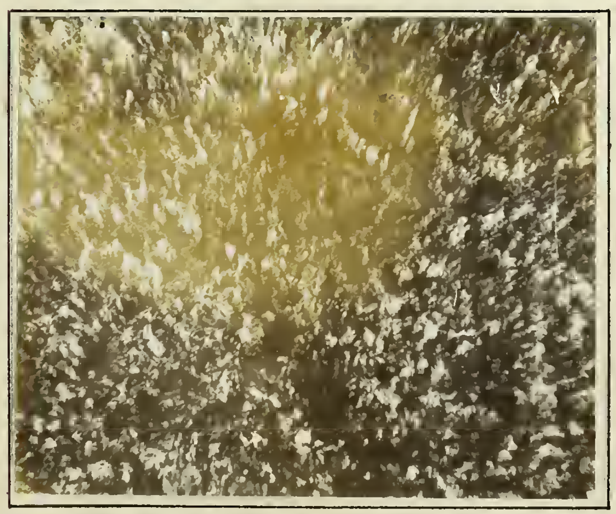
Number 13, (x88)

Heated to 930 ° C

One hour

Cooled in air

Pearlitic



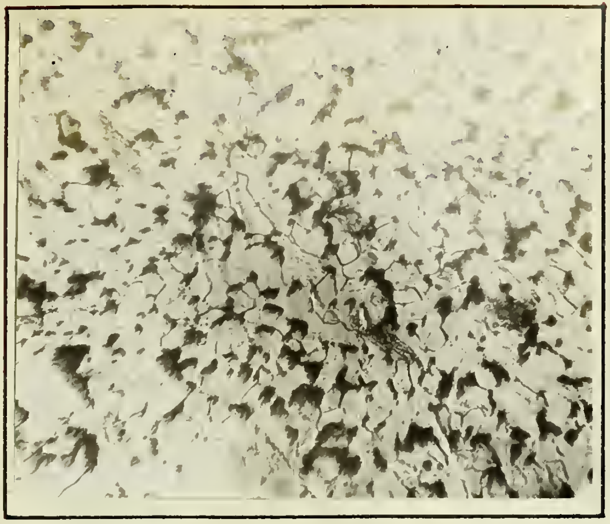
Number 12, (x88)

Heated to 930° C

One hour

Quenched in water

Sorbito-pearlite



Number 11, (x88)

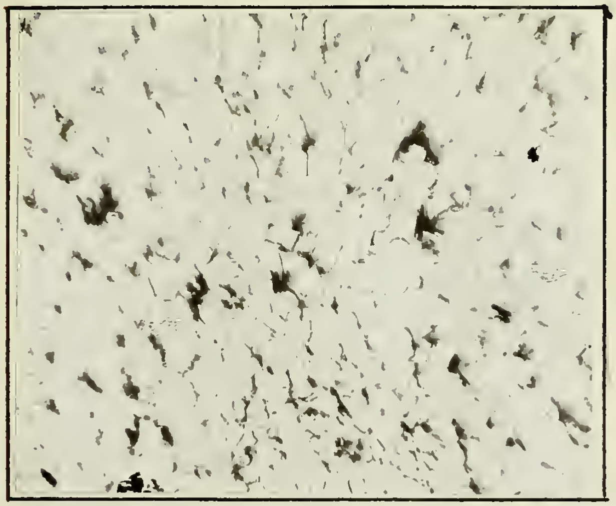
Heated to 930° C

Fifteen minutes

Cooled in furnace

Pearlitic

For grain size



Number 14, (x88)

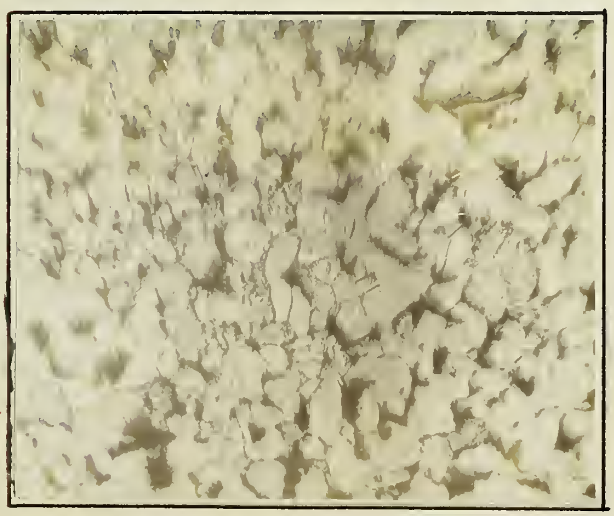
Heated to 930° C

One hour

Cooled in furnace

Pearlitic

For grain size



Number 15, (x88)

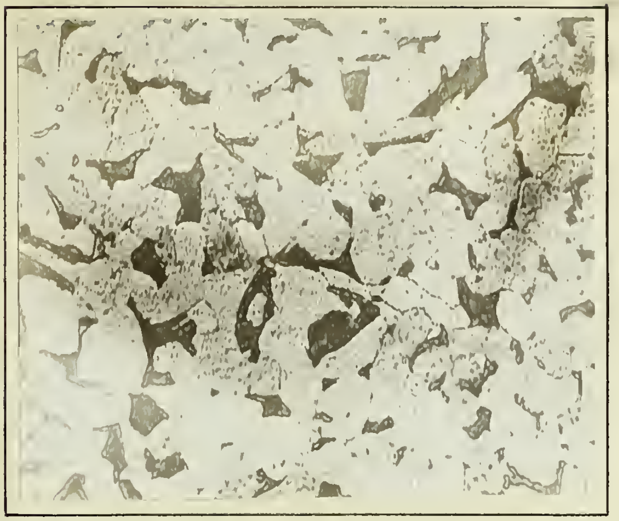
Heated to 930° C

Eight hours

Cooled in furnace

Pearlitic

For grain size



Number 16, (x100)

Heated to 1050° C

Four hours

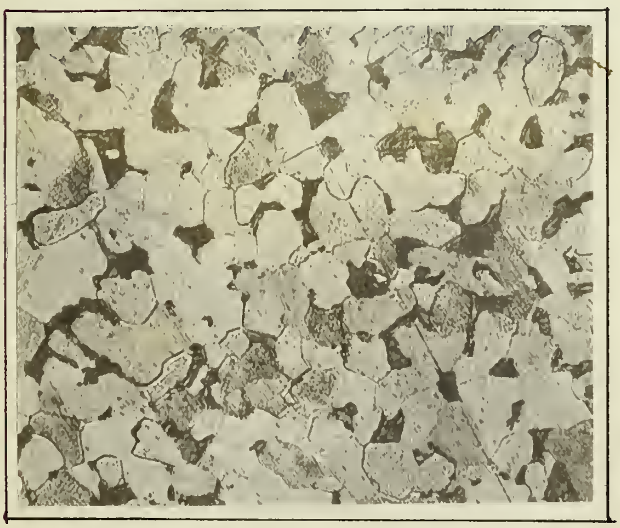
Cooled in furnace

Pearlitic

For grain size

Number 17 heated
three hours

Number 18 heated
two hours



Number 19, (x100)

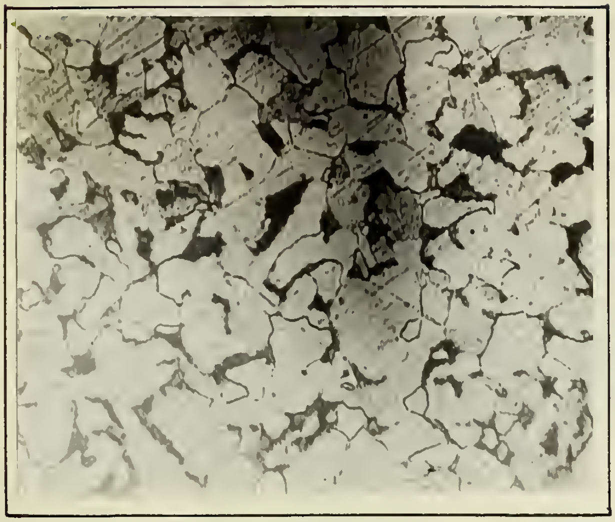
Heated to 1050° C

One hour

Cooled in furnace

Pearlitic

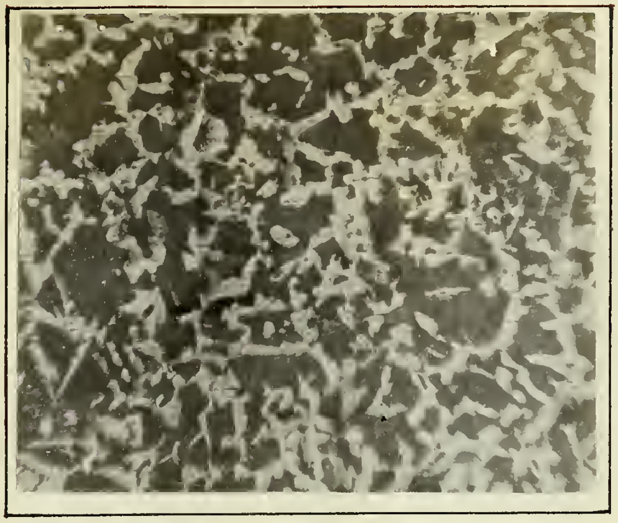
For grain size



Number 111, (x100)
Heated to 1150° C
One hour (gas-furnace)
Cooled in furnace
(more rapid cooling in
the furnace used)
Pearlitic
For grain size

Number 121, (x100)
Heated to 1150° C
Four hours
Cooled in furnace
(Specimen was packed in
$Al_2O_3$ with noble-metal
thermo-couple to ensure
even temperature and
slow cooling)
Pearlitic
For grain size

2. 0.40 % C Steel
Bars 2" x 1"



Number 21, (x88)

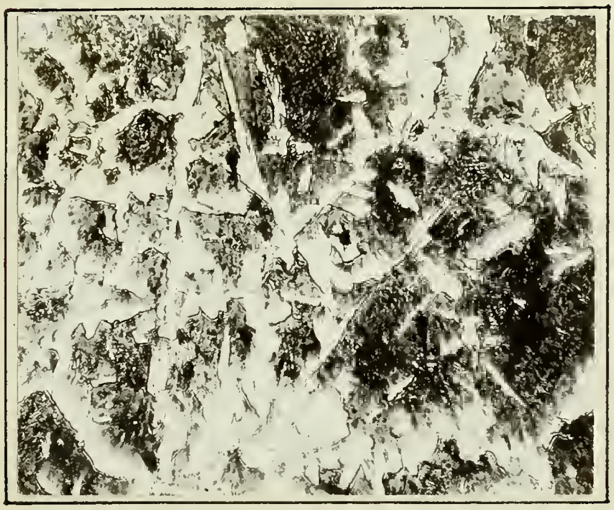
Heated to 900° C

Fifteen minutes

Cooled in furnace

Pearlitic

For grain size



Number 25, (x100)

Heated to 1030° C

Two hours

Cooled in furnace

Pearlitic

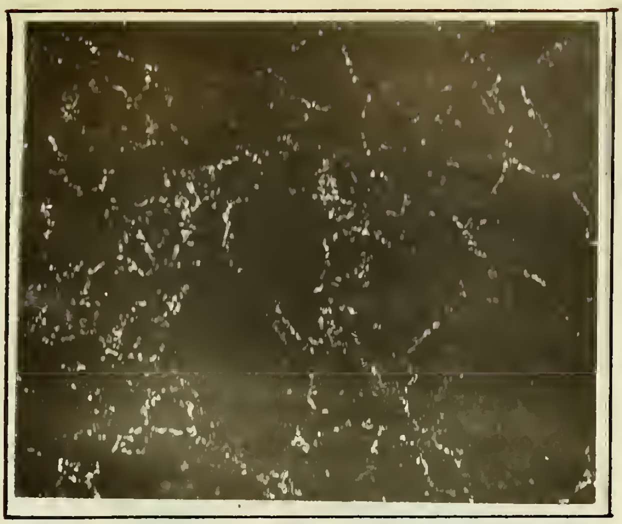
For grain size

Number 25, (x750)

Same as above but

showing pearlitic

structure more clearly



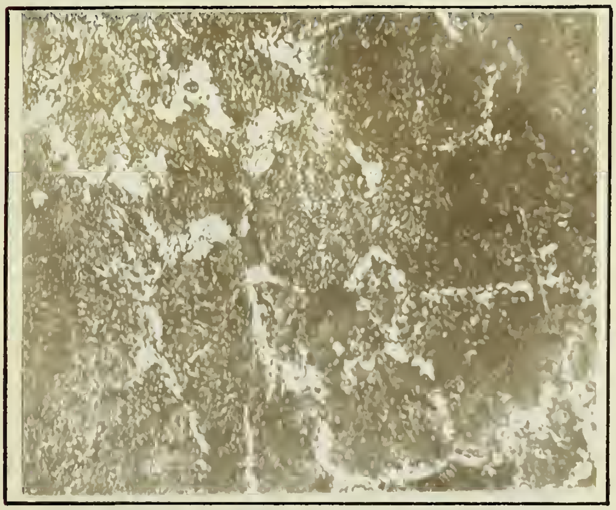
Number 22, (x100)

Heated to 900° C

with No.21, 23 &24

Cooled in air

Pearlitic

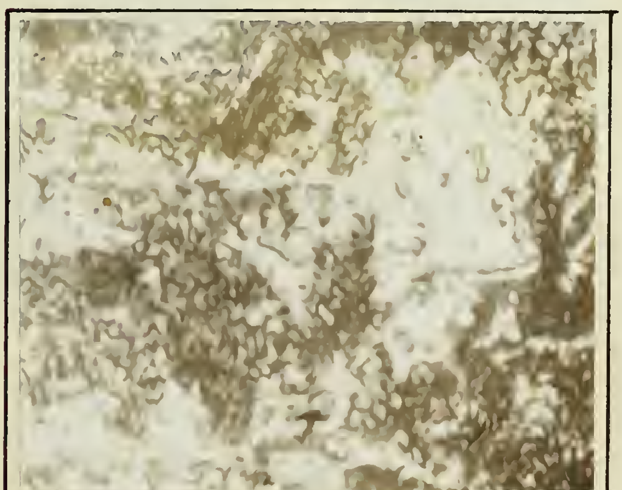


Number 22, (x500)

Same as above

Showing pearlitic

structure



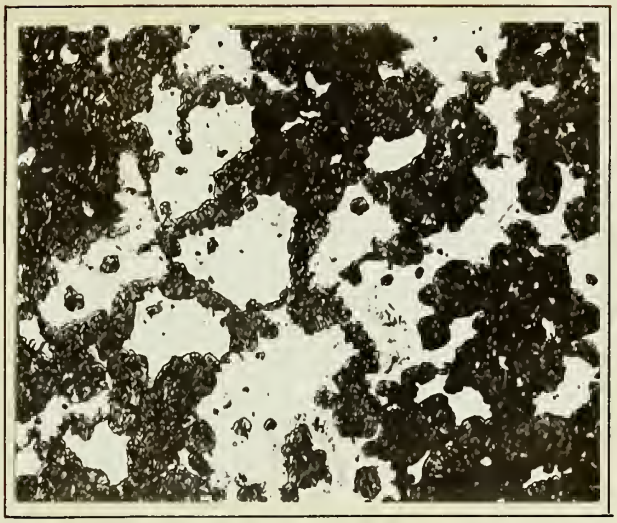
Number 23, (x1500)

Heated to 900° C

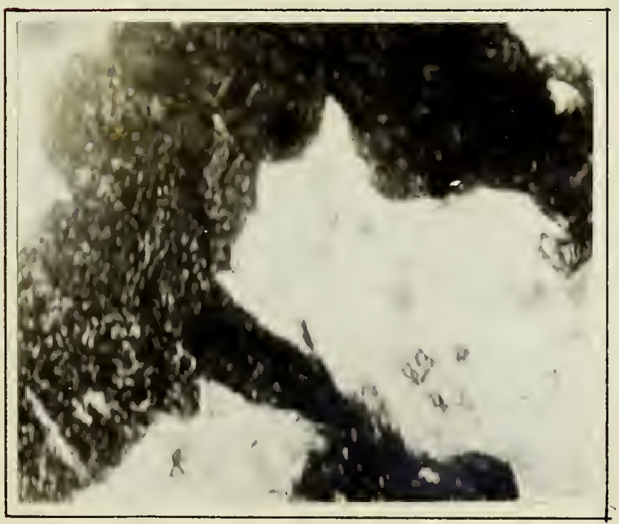
with 21, 22, & 24

Quenched in oil

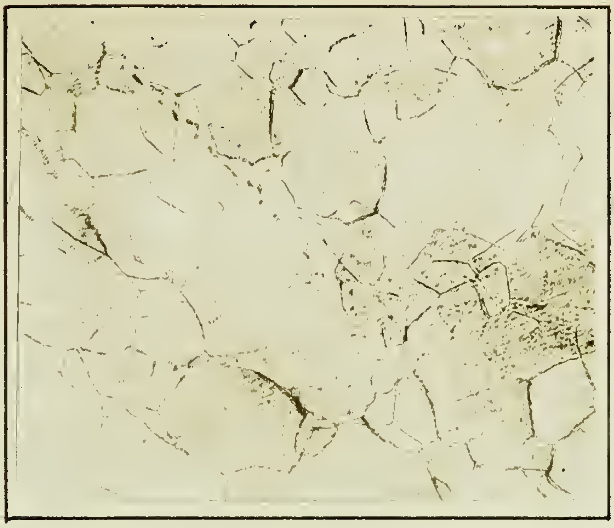
Sorbitic.



Number 24, (x100)
Heated to 900° C
Fifteen minutes
Quenched in water
Troostitic



Number 24, (x1500)
Same as above showing
details of structure



Number 88, (x100)

Alloy after Carpenter

And Elam

Sn - 98.5 %

Sb - 1.5 %

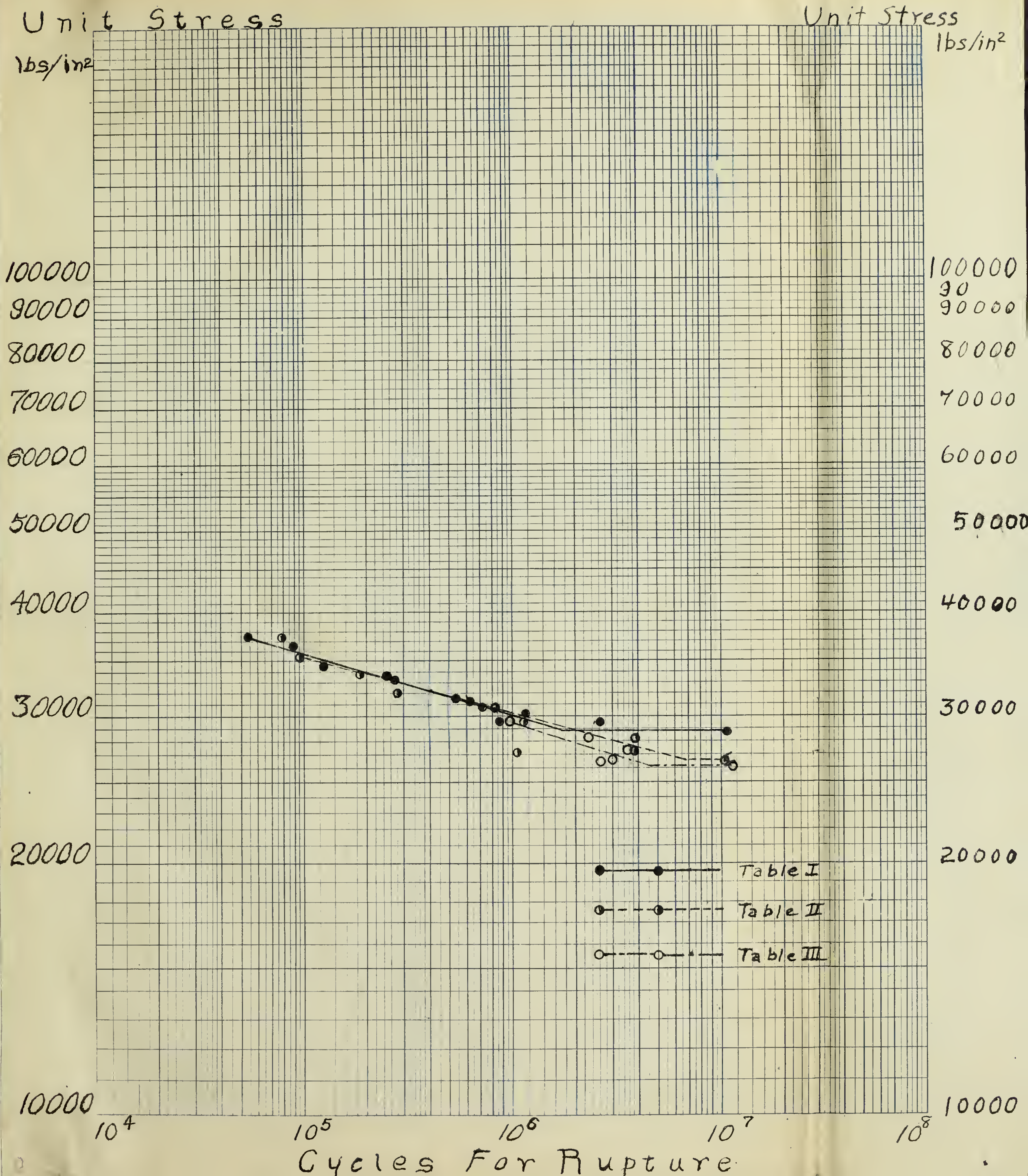
Showing manner of

growth of grains.

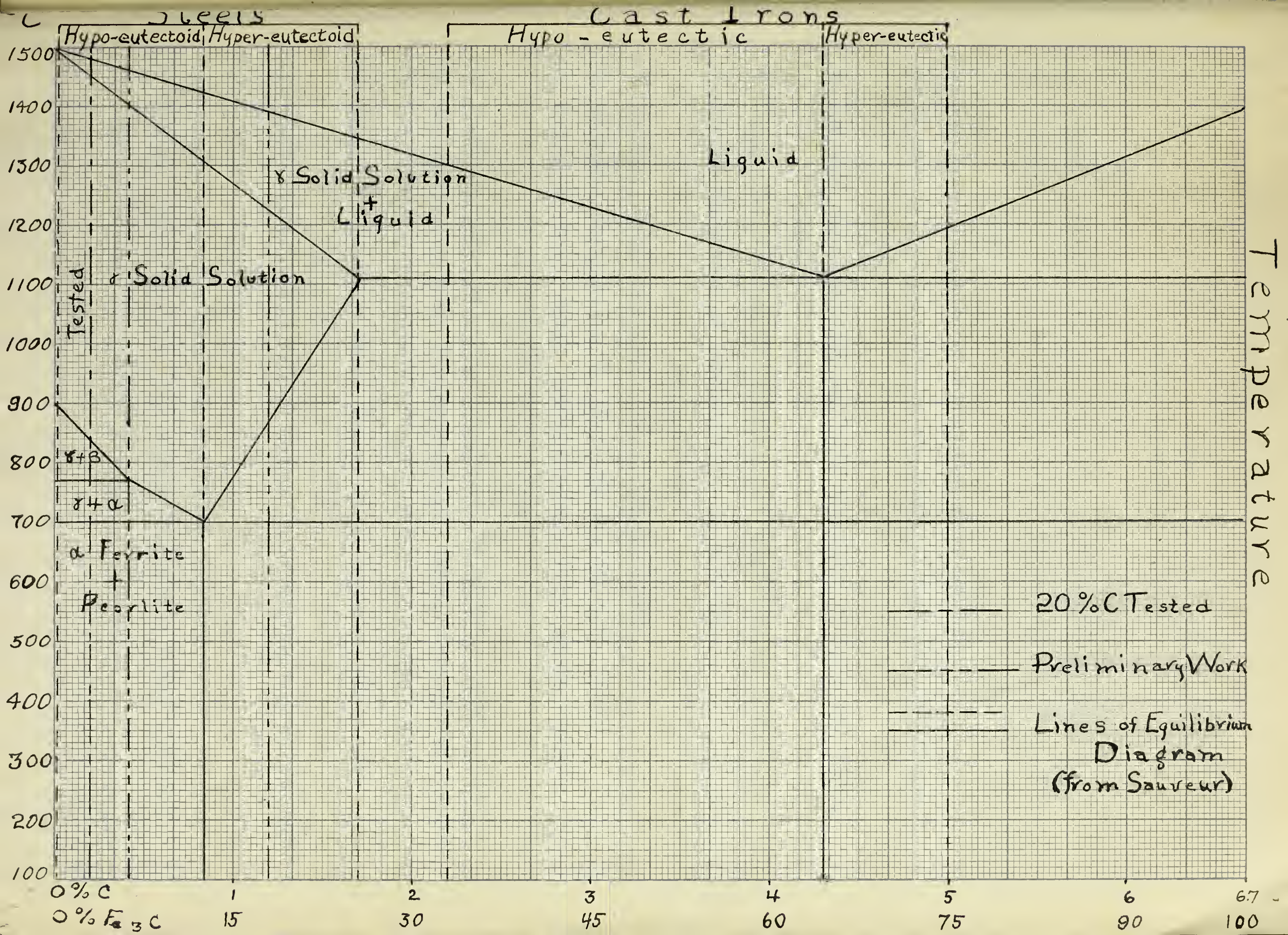
Preparation: Fifteen grams of an alloy of 80 % Sn, 20 % Sb were melted in a crucible and 185 grams of mossy tin were added and the melt poured into a chill. A view of the structure was found by casting on plate glass.

The alloy was annealed at 200° C one hour to permit

complete solution of antimony, polished, etched in $(NH_4)_2S$ and heated thirty minutes at 200 ° C. The crystals turned brilliant colors and the advance of certain crystals at the expense of others could be traced by the new boundary lines, showing that growth takes place by "boundary migration, not by coalescence of crystals". An attempt to repolish the piece effaced all of the old boundaries and left the surface unrecognisable.



Unit Stress
lbs/in2
Unit Stress
lbs/in2
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
100000
90
90000
80000
70000
60000
50000
40000
30000
20000
10000
Table I
Table II
Table III
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$
Cycles For Rupture


C
Steels
Hypo-eutectoid
Hyper-eutectoid
Cast Irons
Hypo - eutectic
Hyper-eutectic
Liquid
γ Solid Solution + Liquid
γ Solid Solution
Tested
γ+β
γ+α
α Ferrite + Pearlite
Temperature
20 % C Tested
Preliminary Work
Lines of Equilibrium Diagram (from Sauveur)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0 % C
1
2
3
4
5
6
6.7
0 % $Fe_3C$
15
30
45
60
75
90
100

# BIBLIOGRAPHY


## Books

1. Hibbard: Manufacture and Uses of Alloy -Steels, (1904)
2. Johnson: Materials of Construction, Fifth Edition, Withey and Ashton.
3. Merriman: Mechanics of Materials, 8vo. (1904).
4. Rosenhain: Introduction to the Study of Physical Metallurgy (1915).
5. Sauveur: Metallography and Heat Treatment of Iron and Steel, (1918)
6. Unwin: The Testing of Materials of Construction, (1910).
7. Upton: Materials of Construction, p. 109-118.

## Periodicals.

8. Andrews: Engineering 80: 235-9, 534-8. (1905)
9. Andrews: Engineering 61: 91-2, 62:35, 68, 118, (1896).
10. Bairstow: Phil. Trans. Royal Society, 210A: 35-55, (1910). (Resume in Unwin, p. 124-5)
11. Basquin: Proc. Am. Soc. for Testing Materials, 10:625. (1910)
12. Carpenter and Elam: Engineering 110: 325-9,424-6,486-90.(1920).
13. Eden, Rose and Cunningham: Engineering 92: 555-60, 693-8,(1911).
14. Ewing and Humfrey: Phil. Trans. Royal Society, 200 A: 225. (1902) 200 A: 241. (1902).
15. Ewing and Rosenhain: Phil. Trans. Royal Society 195 A: 279-301. (1900).
16. Farmer: American Machinist 51: 271-3. (1919).
17. Howard. Proc. Am. Soc. for Testing Materials 7:252. (1907).
18. Joint Committee on Fatigue Phenomena in Metals: